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FINAL REPORT

SHUTTLE CRYOGENICS

SUPPLY SYSTEM

OPTIMIZATION STUDY

VOLUME I

MANAGEMENT SUMMARY

Sections 1 Through 3

CONTRACT NAS9-11330

Prepared for Manned Spacecraft Center
by
Manned Space Programs, Space Systems Division

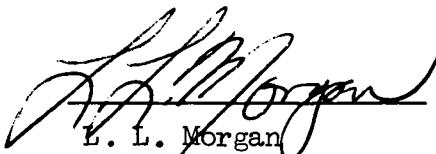
LOCKHEED MISSILES & SPACE COMPANY, INC.
A SUBSIDIARY OF LOCKHEED AIRCRAFT CORPORATION

FINAL REPORT
SHUTTLE CRYOGENIC SUPPLY SYSTEM
OPTIMIZATION STUDY

VOLUME I
MANAGEMENT SUMMARY

Sections 1 through 3

LOCKHEED APPROVAL



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FOREWORD

This Final Report provides the results obtained in the Shuttle Cryogenics Supply System Optimization Study, NAS9-11330, performed by Lockheed Missiles & Space Company (LMSC under contract to the National Aeronautics and Space Administration, Manned Spacecraft Center, Houston, Texas. The study was under the technical direction of Mr. T. L. Davies, Cryogenics Section of the Power Generation Branch, Propulsion and Power Division. Technical effort producing these results was performed in the period from October 1970 to June 1973.

The Final Report is published in eleven volumes*:

- Volume I - Executive Summary
- Volumes II, III, and IV - Technical Report
- Volume VA-1 and VA-2 - Math Model - Users Manual
- Volume VB-1, VB-2,
VB-3, and VB-4 - Math Model - Programmer Manual
- Volume VI - Appendixes

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*The Table of Contents for all volumes appears in Volume I only.
Section 12 in Volume III contains the List of References for Volumes I through IV.

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Section 1

INTRODUCTION

The Space Shuttle System was initiated by the National Aeronautics and Space Administration to provide a low-cost space transportation system through the use of reusable vehicles. The Space Shuttle is to become operational in the 1976-1980 time period. Vehicle configurations employed during the Space Shuttle Phase B definition studies were two-stage fully reusable vehicles, consisting of a booster and an orbiter.

Shuttle Phase B study contract studies, the Space Shuttle contractor selection, and the first year of Shuttle design were performed concurrently with the concept evaluation presented in this report. The two-stage fully reusable concepts were examined exclusively in the Shuttle definition studies until July 1971. The shuttle orbiter propulsion, power, and life support subsystems of the vehicles examined in Phase B utilized cryogenic fluids. The effort in Task 1A Cryogenic Cooling was initiated after the selection by NASA of the Shuttle configuration consisting of a solid rocket boosted orbiter with an external tank. This configuration has storable propellants on-board (no on-board cryogenic propellants) and a hydrazine fueled APU. The fuel-cell and life support systems are cryogenic.

The employment of reusable subsystems introduces potential problems not present in expendable vehicles. Also, the employment of common cryogenics in the propulsion, power, and life support subsystems results in the possibility of integrating the storage, components, and other functions.

The Shuttle Cryogenic Supply System Optimization Study was planned so as to provide definitive subsystem and integrated system information and conclusions at an interim point in the study. An overall study program objective was to determine the manner in which the cryogenic fluid-storage and supply tanks aboard a Space Shuttle Orbiter might be treated as an integrated system, supplying the cryogenics for the Propulsion, Power Generation, and the Life Support subsystems. Another principle object was to develop the Math Model, a series of computer programs to provide assistance in the analysis of Cryogenic Subsystems.

The Final Report is supplemented by a series of documents, referred to as the Task Reports, which have limited distribution as specified by NASA. The Task Reports contain a major portion of the data generated in the contract. A listing of the Task Reports and an index to the information these contain is provided in Section 12 - References.

Lockheed Missiles & Space Company was assisted in the selection and evaluation of components through a subcontract to the AiResearch Manufacturing Company, Division of the Garrett Corp.

The supply systems, which have been examined both as individual subsystems and as integrated systems, include:

- Propellant Supply
 - a. Orbit Injection Propellant (Main Propulsion)
 - b. Orbit Maneuver Propellant
 - c. Attitude Control Propellant
 - d. Purging, Inerting, and Pneumatic Supply
- Power Generation Supply
 - a. Fuel Cell Supply
 - b. Auxiliary Power Unit Supply
- Life Support Supply
 - a. Oxygen Supply
 - b. Nitrogen Supply

Section 2

TECHNICAL APPROACH SUMMARY

Data presented in this report are primarily the results of the performance of Task 1 Concept Evaluation, Task 2 Critical Component Analysis, Task 3 Analytical Characterization, Task 4 System Integration and Mission Application Analysis, and Task 1A Cryogenic Cooling in Environmental Control Subsystem. Information reported is that considered to be necessary (1) to support the tradeoff and sensitivity studies and (2) to provide the component and technology evaluations (3) to explain the Math Model. The supplemental information available in the Task Reports is outlined in Section 12 - References.

2.1 APPROACH TO SUBSYSTEMS AND INTEGRATED SYSTEMS COMPARISONS

Basically, the approach to the comparison of individual subsystems and integrated systems has been as follows:

A. Establish Requirements and Criteria

Requirements and criteria were established principally from the Phase B results. The sources are referenced in Section 5.

B. Subsystem Evaluations

- (1) Establish candidate subsystems
- (2) Collect necessary component information
- (3) Perform detailed subsystem analysis
- (4) Perform sensitivity and tradeoff studies

C. Integrated Systems

- (1) Establish candidate integrated systems
- (2) Modify component information
- (3) Perform detailed analyses
- (4) Perform tradeoff studies

The overall approach is presented in Fig. 2.1-1. Necessarily, the details of the technical approach are much more complex than indicated.

2.1.1 Subsystems Evaluations

In the discussions of the individual subsystems, the detailed approach to analyses, sensitivity evaluations, and tradeoff studies are presented. Sensitivity studies in the performance of the evaluations, were considered to be key factors in determining the importance of concept approaches and technology status. The factors that were continually considered in the study were:

- Sensitivity examinations related to shuttle concepts
 - a. Sensitivity to criteria
 - b. Sensitivity to requirements
 - c. Sensitivity to design variables
- Sensitivity examinations related to technology status
 - a. Sensitivity to material/component performance and lifetime
 - b. Sensitivity to component design
 - c. Sensitivity to analytical techniques

2.1.2 Integrated Systems Evaluations

The Integrated Systems evaluations involved a display of various logical possible combinations followed by analysis of the more reasonable candidates. Analyses of the individual subsystems were employed to ensure that near-optimum subsystem descriptions were utilized.

Reusability and reliability analyses were employed to compare integrated system approaches with nonintegrated systems. The relative reliability and component replacement requirements were examined.

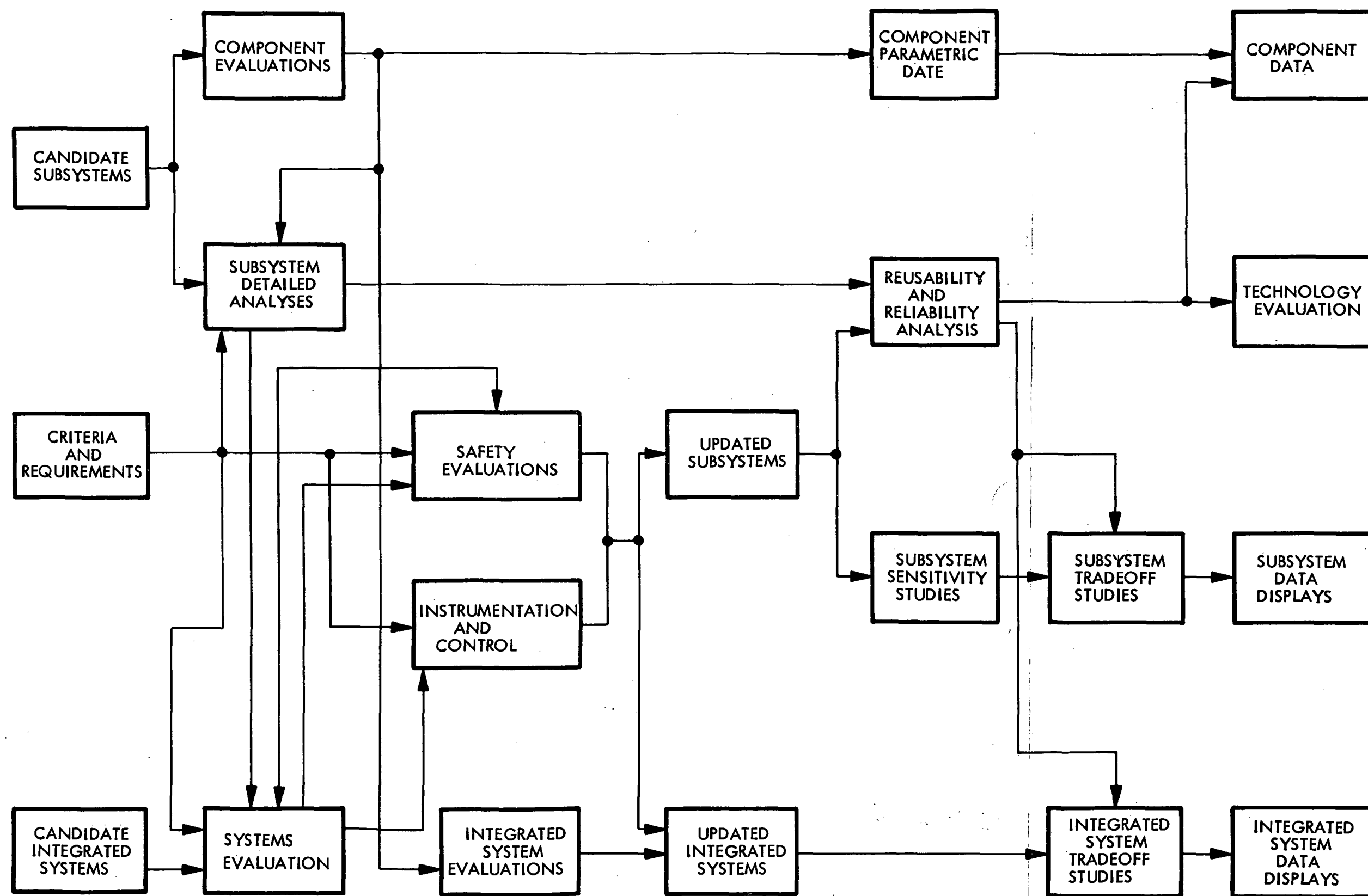


Fig. 2.1-1 OVERALL APPROACH TO CONCEPT EVALUATION

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2.2 APPROACH TO COLLECTION AND EMPLOYMENT OF COMPONENT DATA

The principal division of effort between LMSC and AiResearch in the collection of component data was as follows:

- Lockheed
 - a. Propellant and reactant tanks
 - b. Accumulators
 - c. Heat exchangers on or in tanks
 - d. Vacuum shells
 - e. Feedlines
 - f. Feedline components
 - g. Fluid acquisition devices
 - h. Insulation
 - i. Propellant level and mass sensors
 - j. Pressure and temperature indicators
- AiResearch
 - a. Valves and regulators
 - b. Heat exchangers
 - c. Pumps
 - d. Turbines
 - e. Control units
 - f. Pressure switches

The study program schedule necessitated that LMSC prepare for AiResearch typical subsystem schematics for each of the known subsystem approaches. These schematics provided the likely temperatures, flowrates, and other operating conditions related to the components. Then AiResearch selected and prepared data sheets for each of the components within the subsystems. The selected components represented existing hardware or designs wherever possible. AiResearch examined the likely component malfunctions, and lifetime data. Technology evaluations were made for components that appeared to present possible problems. The information was supplemented with extensive parametric

data on valves, heat exchangers, and pumps. AiResearch invited the participation of other component engineering and manufacturing companies in the preparation of the data, and utilized inputs from these companies.

Structural data for propellant and reactant tanks, accumulators, vacuum shells, and a portion of the feedlines were generated by LMSC using applicable computer programs. Feedline components data were principally obtained from industry survey data.

Insulation data were developed principally from the information presented in previous thermal protection system contract reports. In some instances, it was necessary to apply judgement in the selection of installation degradation. The approach used in the selection of insulation installed properties is considered to have resulted in nominal data for the insulation types under consideration.

Throughout the study, technology status was continually examined and recorded in the monthly reports and reviews. Required technology advancements and developments are presented in this report.

Section 3

SUMMARY OF RESULTS

The objectives of the study have been completed. Information has been provided that allows NASA to select approaches to the Space Shuttle Cryogenic Supply Systems. The major outputs are:

- Evaluations of subsystem and integrated system concepts
- Sufficient information to provide the necessary depth for selection of representative designs
- Documentation and data banks of cryogenic supply system related data and information
- Parametric data and sensitivity studies
- Evaluations of related technology status
- Evaluation of cryogenic cooling in the environmental control subsystems
- Description of the Math Model

3.1 MAJOR STUDY CONCLUSIONS

Several general conclusions resulting from the study were considered to be of major importance. These conclusions were formulated from an overview of the program results:

- Optimum Integrated Systems tend to be in the direction of maximizing common liquid storage. Large supercritical storage systems are not weight effective. The reliability of systems is not significantly affected by integration.
- If integration forces vacuum jacketing of tanks then the resulting additional weight has a major affect on the resulting effectiveness of integration.

- Subcritical storage has an advantage over supercritical storage, which decreases as the quantity of propellant or reactant decreases. It is significantly affected by the quantity of hydrogen stored.
- The shuttle duty cycles are not severe in relation to the potential lifetime of components. Replacement of components as a result of wearout will not be severe.
- Components are available for most of the subsystem applications.
- The technology status related to subsystems and components indicate that with the exception of certain critical components, the required technology developments are minimal.
- Radiators cannot be efficiently replaced by cryogenic cooling techniques.
- Ascent tanks can be employed as heat sinks during ascent and the first hour or so of orbital operation, but the added complexity associated with heat exchanger and circulation systems does not justify the slight weight savings.
- A Cryocycle system does not provide a major advantage, and considerable development would be required.
- The lightest and simplest cooling system for EC/LSS heat control during deorbit and reentry is one which utilizes hydrogen for the expendable fluid. APU cooling can also be accomplished by the use of the same expendable hydrogen. A minimum number of technology efforts would be required if this approach were taken.
- Water and ram air provide the best coolant for a separate APU cooling system if cooling with hydrogen is ruled out.

3.2 INTEGRATED SYSTEMS

Integrated Systems were accomplished in this study by:

- Combining the propellant and/or reactant storage
- Utilization of common components of the distribution subsystem

Integrated System evaluation results indicated that two principal approaches are likely to produce the most weight effective systems:

- System I - Complete Integration

In System I, all propellants and reactants, with exception of the Orbit Injection Propellant Supply, are stored in single tanks. This system is extremely dependent upon propellant acquisition.

- System III - Partial Integration

In System III, the basic integration mode is:

- a. Orbit Injection Propellant is stored subcritical in separate tanks.
- b. Orbit Maneuvering Propellant Supply/Attitude Control Propellant Supply in a common tank.
- c. Auxiliary Power Unit reactant separately stored in a subcritical tank.
- d. Fuel Cell/Life Support Supply stored in a supercritical common tank.

3.3 ORBIT MANEUVERING PROPELLANT SUPPLY

The Orbit Maneuvering Propulsion has the function of providing orbit transfer maneuvers and deorbit. The logistic resupply mission was employed as the baseline mission. This mission requires approximately 1500 ft/sec. In accordance with Phase B groundrules, the propellant supply system was sized to provide 2000 ft/sec.

Two engines were considered in the study, the RL-10A3-3 and an advanced engine. Both the integral engine pump (pump-at-the-engine) and the pump separate from the engine (pump-at-the-tank) were evaluated as concepts.

The Orbit Maneuvering Propellant Supply was examined extensively. Some of the results and conclusions are:

- The concepts employing pump-at-the-tank result in lower weight subsystems than pump-at-the-engine.
- Helium pressurization results in lower pressurization subsystem weight than does propellant gas pressurization.
- Pressurization with propellant gasses (GO_2/GH_2) produces several undesirable factors
 - (a) It is sensitive to duty cycle.
 - (b) GO_2/GH_2 pressurization can only be employed with orbital propellant.
 - (c) The propellant gases must be heated and the propellant acquisition thermal problems are more serious.
- Vacuum-jacketed tanks and lines are heavier, but protect reusable insulation systems.

- The approach to conservation of feedline propellant between engine operations, coupled with feedline sizing, results in significant weight sensitivities.
- Use of cascade tanks results in some weight penalty as compared to dual tanks with separate feed systems. (Propellant utilization in dual tanks is assumed to be satisfactorily controlled with level sensors. Cascading of tanks could place less stringent requirements on propellant utilization and control.)
- The employment of start tanks is not applicable to Orbit Maneuvering Propellant Supply subsystems unless the subsystems are integrated.

3.4 ORBIT INJECTION PROPELLANT SUPPLY

The Orbit Injection Propulsion provides for the initial ascent of the orbiter. The baseline mission employed required injection into a 100 n mile orbit. The evaluations performed on the Orbit Injection Propellant Supply were to examine particular subsystem functions rather than to attempt to optimize the entire subsystem.

The Orbit Injection Propellant Supply examinations resulted in several conclusions which were considered to be significant:

- The comparison of intermittent pressurization flow with continuous pressurization flow (excess vented) results in comparable results.
- Common vent and pressurization lines are satisfactory.
- The prepressurization of the propellant tanks may be accomplished with on-board stored helium or propellant gases without a significant penalty.

- Pressurization parameters (such as residuals, mass flow-rate, etc.) are not sensitive to insulation thickness (and subsequently, thermal conductivity.)
- Feedline temperature control by circulation is more effective than by insulation.

3.5 ATTITUDE CONTROL PROPELLANT SUPPLY

The Attitude Control Propulsion has the function of maintaining attitude for limit cycling, docking, and similar maneuvers and for limited translation. Systems using Gas/Gas in the thrusters and Liquid/Liquid in the thrusters were examined.

The Gas/Gas Attitude Control Propellant Supply Subsystems were based upon NASA technology contracts. The Liquid/Liquid Systems were evaluated parametrically. Some of the results of the studies are as follows:

- Results of the Gas/Gas Attitude Control Propellant Supply evaluations indicated that subcritical storage of the propellants results in lower dry weights than supercritical storage of the propellants.
- Liquid/Liquid Attitude Control Propellant Supply subsystem weights are comparable to Gas/Gas ACPS subsystem. The weight of Liquid/Liquid ACPS subsystems are directly related to the performance of the bellows.
- Electrical motor-driven pumps are applicable to the ACPS subsystem. Dry weights are increased, but overall system weight is comparable.

- Two of the major technology problems identified were related to the ACPS subsystem: 1) All axes propellant acquisition, coupled with the ACPS feed system requirements, was considered as possibly the major requirement for technology advancement; 2) The ACPS pump was identified as another major technology requirement.

3.6 AUXILIARY POWER UNIT SUPPLY

The Auxiliary Power Units are oxygen/hydrogen turbines providing power to the hydraulic system and alternators. As a result of examination of the results of related Auxiliary Power Unit technology programs, the Gas/Gas APU feed system was selected for evaluation rather than Liquid/Liquid feed to the gas generators. Storage of the reactant considered both subcritical (liquid) storage and supercritical storage. Examination of the Auxiliary Power Unit Supply required a tradeoff involving mixture ratio, gas generator pressure, and redundancy approach (number of APUs).

The major conclusions resulting from these studies were as follows:

- The use of supercritical storage of the reactant resulted in substantial weight penalties as compared to subcritical storage.
- The effects of O/F ratio on the subsystem were relatively small.
- The subcritical (liquid) storage subsystems required a pump while the supercritical subsystems were pressure fed. This factor tended to optimize subcritical storage at the higher turbine inlet pressures (>900 psia).
- The supercritical storage subsystems tended to optimize at lower pressures and to be affected by mixture ratio. With an O/F of 0.5 the optimum turbine inlet pressure was near 300 psia and with an O/F of 0.9, the optimum was near 600 psia.

- Reactant acquisition for the APU in integrated systems adds a substantial requirement to the acquisition device. During ascent, the problem is less severe because of the full reactant loading. However, during reentry the APU reactant must be acquired in large tanks under accelerations up to 2g. Special provisions are necessary for this problem.
- The Auxiliary Power Unit pump should be capable of running continuously when the APU is required. This results in special pump considerations.

3.7 FUEL CELL SUPPLY

The Fuel Cell Supply provides the reactants for the fuel cells which supply the principal electrical power for the orbiter. The reactants were examined for both subcritical (liquid) storage and supercritical storage.

Significant conclusions resulting from the study were:

- Comparisons between supercritical and subcritical storage indicated that these were comparable from the standpoint of subsystem weight. This would indicate that supercritical storage is preferred, since propellant acquisition and thermal control requirements would be less critical.
- The Fuel Cell Supply system was found to be affected by the reusability of components. The long-operating time of this system, relative to the propulsion systems, requires more component replacements.
- There are no advantages to a low pressure fuel cell supply.
- Fuel cell purging to remove helium (which has entered through being dissolved in LO_2 or LH_2) is not a significant penalty.

3.8 LIFE SUPPORT SUPPLY

The Life Support Supply provides the oxygen and nitrogen required for the cabin atmosphere. The Life Support Supply has relatively little effect on the cryogenic supply subsystems.

The evaluations produced the following conclusions:

- A tradeoff study of supercritical and subcritical storage indicates comparable weights, with a slight advantage for supercritical storage.
- The LSS subsystem must operate continuously, as the Fuel Cell subsystem. Therefore, a substantial number of component replacements result.

3.9 PURGING, INERTING, AND PNEUMATIC SUPPLY

The Purging, Inerting, and Pneumatic Supply subsystem provides for the following functions:

- Helium Subsystem (On-Board Storage)
 - ● Main engine pneumatic and purging
 - ● RL-10 pneumatic and purging
 - ● Pneumatic valves
 - ● Hydrogen tank insulation purging
- Nitrogen Subsystem (On-Board Storage)
 - ● Hydrogen purging (leakage regions)
 - ● Oxygen tank insulation purging
 - ● Airbreathing fuel oxygen removal and tank inerting
 - ● Hydrogen tank inerting (if employed)

- Nitrogen Ground Purging
 - ● Purging of hazardous regions
 - ● Purging for moisture exclusion

The Purging, Inerting, and Pneumatic Supply subsystem results are closely related to the requirements.

Helium Subsystems

The evaluation of the helium subsystems indicated:

- Helium subsystem requirements and sizing are principally dependent upon the main engine requirements.
- Storage of helium at LH_2 temperature is the most satisfactory approach. The only disadvantage is that the required heat exchangers to heat the helium are relatively large in order to supply the required flowrates.

Nitrogen Subsystems

Nitrogen subsystem evaluations indicated:

- The nitrogen subsystems are very dependent upon (1) the amount of purging to dilute hydrogen leakage and (2) whether hydrogen tank inerting is employed.
- Subcritical storage of nitrogen appears to be the most satisfactory storage method.
- For ground purging of the orbiter bays which contain cryogenics, it was determined that the main distribution line could be less than 5 inches in diameter and operate at approximately 100 psia.

3.10 CRYOGENIC COOLING IN ENVIRONMENTAL CONTROL SUBSYSTEMS

Initially the study was designed to determine ways in which the available large quantities of cryogenics could be used to absorb the heat generated by the electronics and the crew and to utilize this heat beneficially to condition the cryogenics for their ultimate use. It was anticipated that the orbiter radiators could be eliminated or at least reduced in size. Furthermore, it was expected that if the radiators were not eliminated, the on-board cryogenics would play a key role in providing the cooling function at times when the radiators were not deployed.

After the task was partially completed, there was a change in the Shuttle concept from a two-stage reusable system to the current Shuttle concept of Solid Rockets/External Tank/Orbiter, which has only fuel cell and life support cryogenics in the orbiter.

The initial studies were begun with the just enumerated purposes in mind and in the following major categories:

- No work to be removed from the cryogenics
- Sufficient work to be removed from the cryogenics to power compressors or pumps
- As much work as practical to be removed from the cryogenics to supplement vehicle power

General system concepts were defined to help evaluate these major categories and are:

- Expel cryogenics overboard directly after absorbing heat
- Store heated cryogenics in accumulators

- Store heated cryogenics in ascent tanks
- Feed Cryogenics direct to user after heating

Studies in these general areas were initiated and effort had proceeded for a few months when the design change was announced. At that time the effort was redirected to areas that could still benefit by studies related to environmental systems cooling. These studies included investigation of:

- Heat capacity of cryogenic droptanks
- Cryocycle system comparison
- APU Systems comparison
- Environmental systems cooling techniques for use during reentry and ferry phases of the flights

From the initial studies, the following conclusions were developed:

- Heat balance studies. A comparison of the rate and cumulative heat generated with the rate and cumulative cryogenics usage showed that a basic incompatibility exists and that cryogenics cannot be used to absorb the generated heat as they are required for use.
- Cryogenics usage management. Several comparisons were made of concepts that used the cryogenics in different ways and compared these concepts with a baseline system which employed radiators. The baseline system utilized dedicated vented hydrogen to provide cooling when the radiators were inoperable. One of the studied concepts utilized dedicated hydrogen in addition to normally vented hydrogen for cooling instead of radiators. This turned out to be 1200 lb heavier than the baseline but the system did

not have the deployment and operational problems associated with the radiators.

Another concept used accumulators to store the ACPS cryogenics after they had been conditioned by the EC/LSS heat in conjunction with dedicated hydrogen for additional cooling. This system turned out to be about 8400 lb. heavier than the baseline system.

Other concepts which utilize larger accumulators were considered but they were extremely heavy.

Optimization of combinations of low flowrate and high flowrate studies were started but not completed because of the change in Shuttle configurations. Approximations indicated that such a system would not be significantly lighter than the first one mentioned above.

- Heat capacity of ascent tanks and residuals. The analysis was oriented toward determining the practicability of using the tanks (1) to store environmental control and equipment waste heat and (2) to make this heat available at an appropriate rate for conditioning of ACPS propellants. The analysis showed that over 2 million Btu could be absorbed by the ascent tanks before a temperature of 500°R would be reached and that in order to transfer heat from the tanks to the ACPS propellants at the high rates required large heat exchangers and compressors would be necessary. This system appeared cumbersome and little hope was felt that it would result in significant weight advantages.

From the studies that are applicable to the current Shuttle configurations, the following conclusions were reached:

- Cryogenic/Freon heat exchanger. Early in the study, an effort was initiated with the AiResearch Manufacturing Company to parametrically investigate several hydrogen/Freon and oxygen/Freon heat exchangers capable of transferring EC/LSS heat to the cryogen fluids. Many of the parameters were selected on the basis of pressure and flowrates established by the Phase B Shuttle contracts. However, the parameters were broad enough to be applicable to current Shuttle design conditions. The study showed that dryogenic hydrogen/Freon and oxygen/Freon heat exchangers could be adequately designed, and significant development problems are not expected. The heat exchangers are compact and light.

- Radiators supplemented with refrigerator. A brief study was made to evaluate the extent to which a refrigerator could supplement the radiator for rejection of heat from the environmental thermal control system. The main idea is to increase the average radiator temperature by using an active refrigerator and thereby reducing the radiator area. The general conclusion is that a refrigerator will not sufficiently aid the system to warrant the added complexity; however, for configurations in which radiator area is a significant problem, there may be no other choice.

- Cryhocycle comparisons. Comparisons were made between a baseline system consisting basically of fuel cells for power and radiators for heat rejection and Cryhocycle system which uses a cryogenic hydrogen expander to provide both power and cooling. The resulting weight comparisons showed that the baseline system was lighter by about 442 to 534 lb., depending on the basic data. However, the Grumman Corporation also performed a cryhocycle study with slightly different assumptions and showed the two systems to be approximately equal in weight.

- APU Comparisons. Three APU systems were compared on the basis of weight. Functions of both power generation and EC/LSS cooling during deorbit and reentry were considered. The three types of APUs and a cooling system which uses dedicated cryogenically stored hydrogen that is heated and vented overboard, a hybrid hydrogen APU that expands part of the hydrogen that is used for cooling, and a cryogenically stored oxygen and hydrogen-supplied APU that utilizes the EC/LSS and APU generated heat to condition the reactants. The study showed that the oxygen-hydrogen APU was the lightest by 770 lb. as compared to the hydrazine APU system, and the hybrid system was 320 lb. lighter than the hydrazine APU system.
- Ram Air Cooling. To better define how much dedicated fluid would be required during reentry, an investigation was made to (1) determine the capability of achieving rejection of the EC/LSS heat to air during descent by means of passing ram air between the folded and stowed radiators and (2) the possibility of cooling the hydraulic oil only by means of a fin-and-tube oil-to-air heat exchanger.

For the first study, it was concluded the ram air could not adequately be used to cool the stowed EC/LSS radiators. This was due to the large area requirements associated with ram air cooling of the Freon in the radiators, and the relatively low Freon-to-air temperature difference, high heat loads, and absence of fin convective effects, and the inability of achieving the desired Freon outlet temperature below about 13,000 ft. The results of the second study indicated that ram air cooling over 17 in. by 17 in. by 3 in. thick heat exchanger could be used for APU cooling below 56,000 ft.

- EC/LSS - APU cooling during reentry. Several concepts to provide cooling for the EC/LSS and APU systems during deorbit and reentry were reviewed. The application of these concepts to other phases of flight, such as the horizontal ferry flights and flight tests, was also evaluated. Of the several systems that employ expendable fluids (hydrogen, water, ammonia, etc.) for cooling, the hydrogen system appears to be the best. It is light and requires a minimum of new technology for development and is applicable to all phases of flight. Various compressor-expansion machines were considered, and the one that appears best is a closed-cycle vapor compression refrigerator that uses water for cooling outside the atmosphere and air within the atmosphere.

3.11 MATH MODEL

The Math Model for cryogenic systems is a flexible, broadly applicable systems parametric analysis tool. The program will effectively accommodate systems of considerable complexity involving large numbers of performance dependent variables such as are found in the individual and integrated cryogen systems. Basically, the program logic structure pursues an orderly progression path through any given system in much the same fashion as is employed for manual systems analysis.

The system configuration schematic is converted to an alpha-numeric formatted configuration data table input starting with the cryogen consumer and identifying all components, such as lines, fittings, valves, etc., each in its proper order and ending with the cryogen supply source assembly. Then, for each of the constituent component assemblies, such as gas generators, turbo machiner, heat exchangers, accumulators, etc., the performance requirements are assembled in input data tabulations. Systems operating constraints and duty cycle definitions are further added as input data coded to the configuration operating sequence. Characteristic performance data over the range of temperatures, pressures and flow rates of interest for each of the functional component assemblies, is input

to the program or table lookup data arrays to be called as needed in the analysis sequences. The use of table lookup data combined with closed-form solution analysis, where needed, permits the rapid computation of the desired parameters as the analysis proceeds through the system configuration.

The program will size the system to fit the operating demands and constraints and produces as output the component and system hardware size and weight, propellant (or reactant) weight, vented fluid weight, and such analytical information (i.e., computed performance values) as may be desired. The analytical results are displayed both as time dependent data tabulations and summary table data.

3.11.1 Program Purpose

The intended purpose of the program is to provide an analytical tool which permits rapid parametric evaluation of the various types of cryogenics space-craft systems currently under study in the national space program. The mathematical techniques built into the program provides the capability for in-depth analysis (combined with rapid problem solution) for the production of a larger quantity of soundly based trade-study data than normally would be obtained in hand calculations. Program flexibility in accommodating advanced systems resides in its modular type programming which permits program growth with simple addition of new subroutines and the addition of variables to existing common banks. Conversely, the program is easily dismantled if it is desired to limit analysis to only one or two systems and utilize a smaller computing machine.

In summary, the purpose of the program may be said to be that of providing an improved general analysis tool for cryogen technology applications.

3.11.2 Program Structure

The Integrated Math Model for cryogenic systems consists essentially of three major sections as illustrated in Figure 3.11-1. Within each of the major

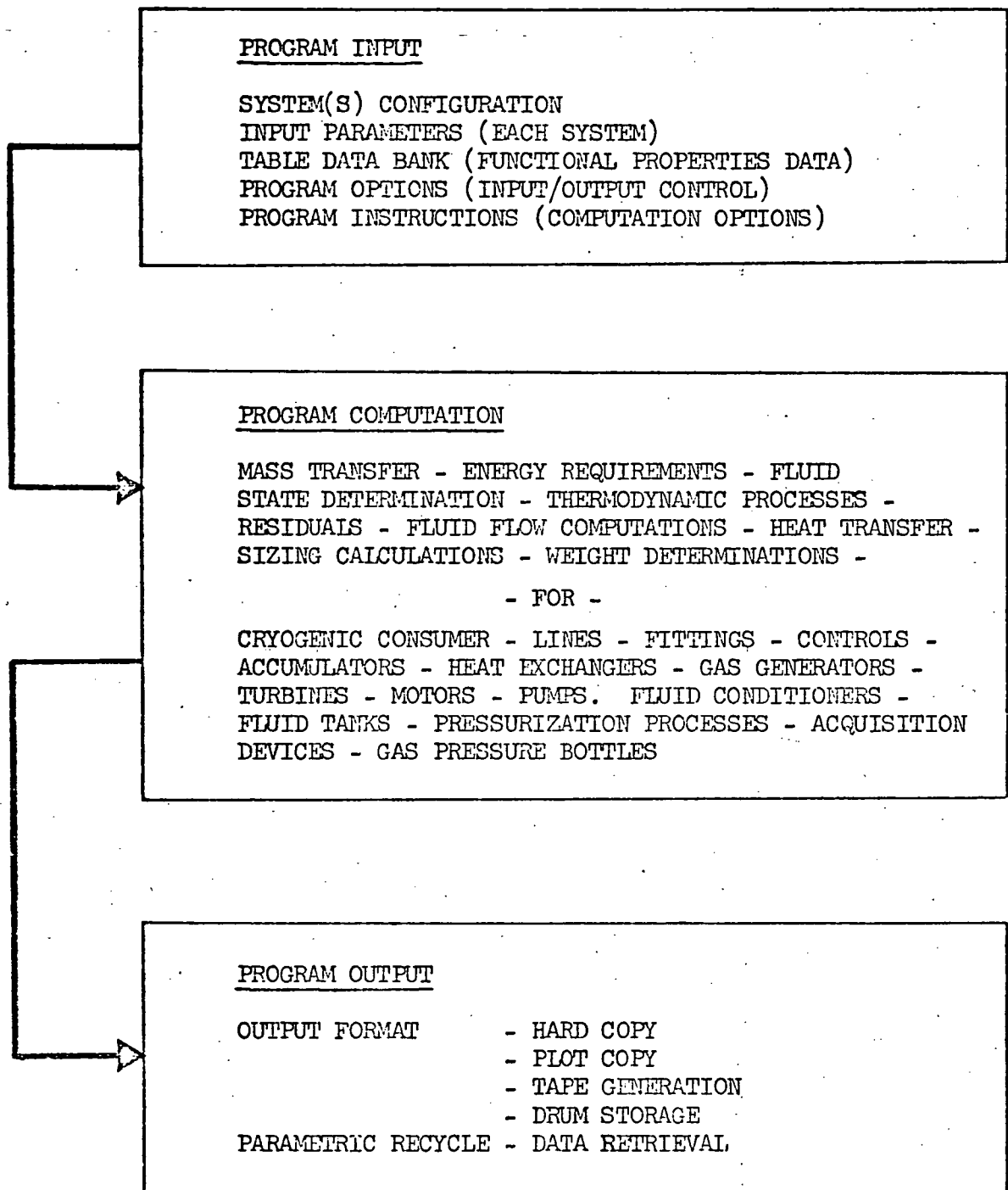


Figure 3.11-1 Major Program Structure

sections the structure is further broken into block subsections, each of which is reserved for specific functions of data management, data utilization or analytical data display.

3.11.2.1 Program Input Data Logic

Of necessity, the program requires a rather large data bank capable of providing characteristic performance data for the wide variety of component assemblies found in typical cryogen systems.

Program data requirements for the Integrated Math Model are divided into two types. The first type consists of the "semi-permanent" data tables which the program employs to compute performance, weight, property, and other characteristics as a function of up to four variables per run.

The table data bank contains the necessary component performance characterization data for the system configurations to be considered, as well as the required cryogen properties data and required material properties data.

The "source data", as obtained, is verified as being authoritative, and is then processed into a formatted tabular array which specifies the table name, ID codes, the dependent variables, and the independent variables - in order of use. The tabulated array data is carefully ordered such that curve fitting routines can extrapolate data points with good accuracy and speed. The prepared data array is punched into data card decks and verified for correctness. The procedure is illustrated in Figure 3.11-2. All data tables are logged as to reference, source, date of data acquisition, and pertinent data limitations such as range of application, etc.

Since a large volume of table data can be required by the program, a unique data management set of subroutines is employed to retrieve any particular table and extract the required information with remarkably high speed and accuracy. Additionally, a machine plotted and/or printed tabulation "echo" of the tables can be requested for easy table input checking.

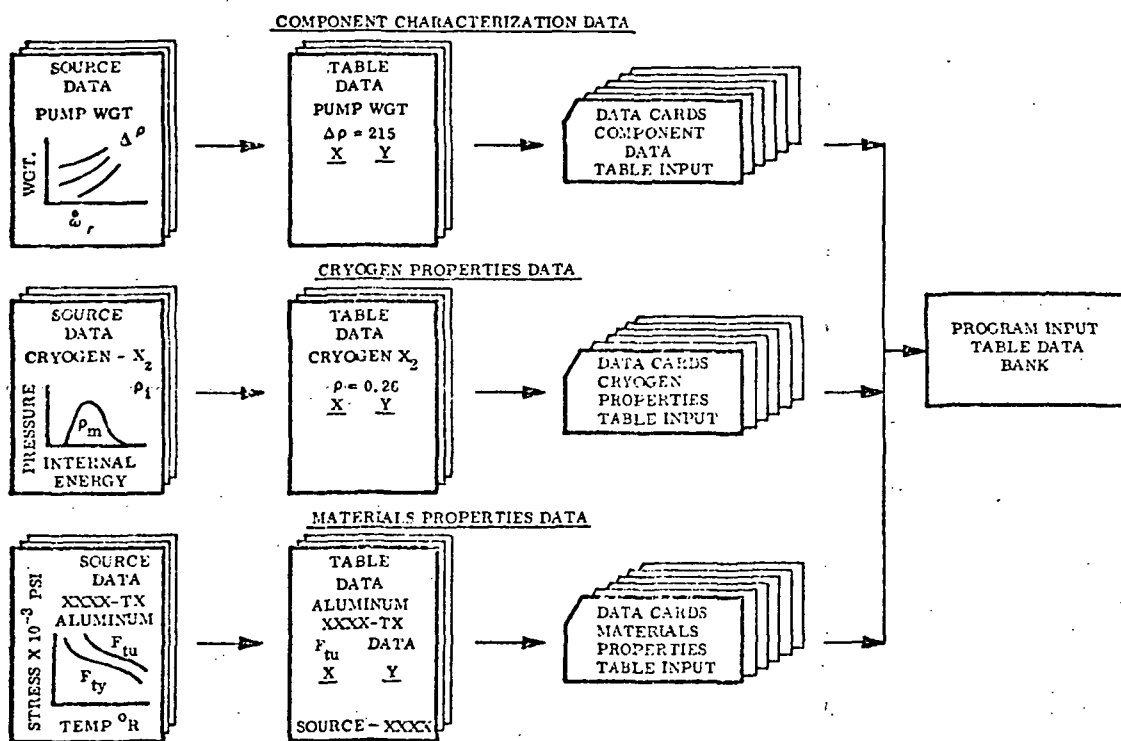


Figure 3.11-2 Source Data Preparation Sequence

The program currently contains forty-six tables and currently will accommodate up to fifty tables for a total of 7000 words.

The second type of input data is "variable" and contains the variable input parameters which may be perturbed for parametric system studies. These data include duty cycle characteristics, configuration description, and operational requirements of the system being studied. The variable input values are printed out just prior to the system computed data output as a means of input verification.

The general program input data requirements by type of data and source is illustrated in Figure 3.11-3.

3.11.2.2 Program Computation Logic

In order for the Integrated Math Model to accommodate the possible range of cryogenic systems likely to be considered and perform as a general systems analysis tool, the following three premises are established:

- (1) Any logical combination of supply tanks, lines, fittings, valves, regulators, heat exchangers, gas generators, pumps, accumulators, and "cryogen-consumer" components can be specified as a system configuration point.
- (2) The "cryogen-consumer" component may be any of the components being supplied with cryogenic fluids.
- (3) An integrated cryogenic system may contain a number of similar and/or different cryogen subsystems to be fed from a common cryogen supply source.

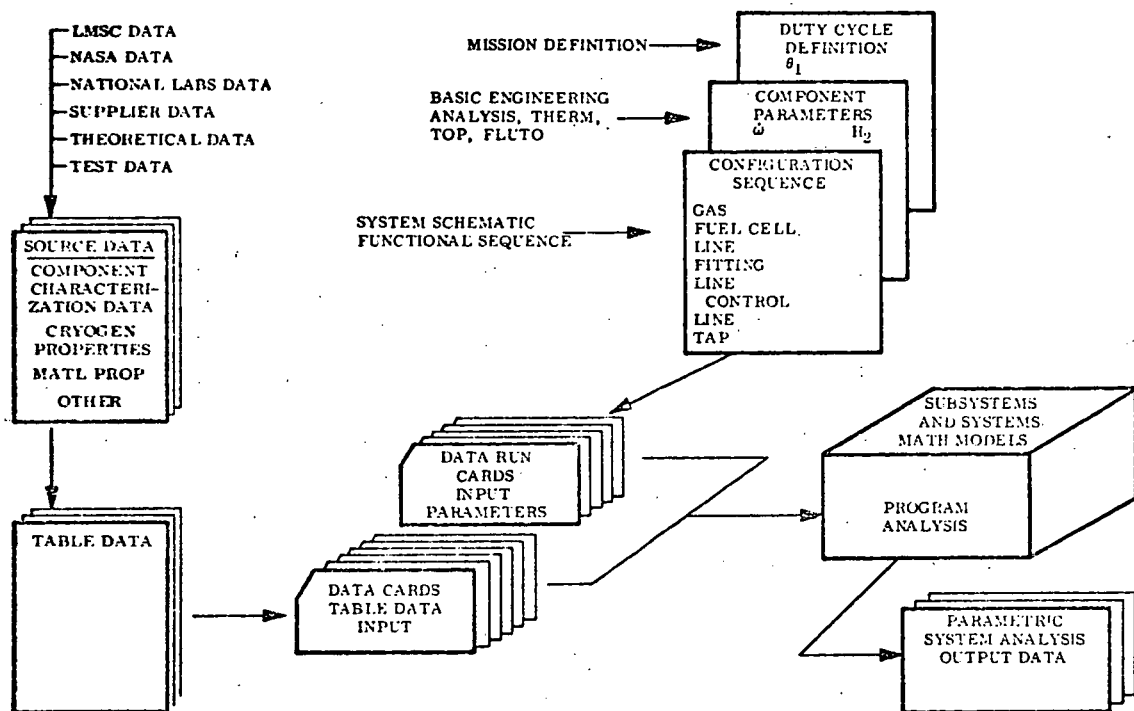


Figure 3.11-3 Program Input Requirements By Type of Data

Although these premises appear to force the generation of a very large program, an examination of the six basic individual cryogen system concepts reveals a marked similarity and commonality of components by kind. Table 3.11-1 illustrates adequately the fact that there are less than twenty-five kinds of major component assemblies to be considered, additionally, the temperatures, pressures, and flow rates are for the most part within reasonable range spans, thus further reducing the quantity of data to be manipulated.

Table 3.11-1

CRYOGEN SYSTEMS - COMPONENT SIMILARITY BY KIND

COMPONENT LIST	ACPS		APU		FUEL CELL		EC/LSS		OMS	
	SUBCR	SUPCR	SUBCR	SUPCR	SUBCR	SUPCR	SUBCR	SUPCR	P.A.E.	P.A.T.
ENGINE (MAIN)									•	•
ENGINE (AUXILIARY)	•	•								
TURBINE - GENERATOR			•	•						
FUEL CELL					•	•				
CABIN ATMOSPHERE							•	•		
ENVIRONMENT CONTROL										
LINES	•	•	•	•	•	•	•	•	•	•
FITTINGS	•	•	•	•	•	•	•	•	•	•
VALVES	•	•	•	•	•	•	•	•	•	•
REGULATORS	•	•	•	•	•	•	•	•	•	•
ACCUMULATORS	•	•	•	•	•	•	•	•	•	•
HEAT EXCHANGERS	•	•	•	•	•	•	•	•	•	•
HEAT SOURCES	•	•	•	•	•	•	•	•	•	•
GAS GENERATORS	•	•	•	•	•	•	•	•	•	•
TURBINES	•	•								
MOTORS			•	•						
PUMPS	•	•	•	•	•	•	•	•	•	•
TANKAGE	•	•	•	•	•	•	•	•	•	•
THERMAL CONDITIONING UNIT	•	•	•	•	•	•	•	•	•	•
PRESSURE CONTROL	•	•	•	•	•	•	•	•	•	•
ACQUISITION	•	•	•	•	•	•	•	•	•	•
GAS STORAGE			•	•					•	•
CIRCULATION PUMPS				•	•	•				

Appendix to Section 3

DISCUSSION OF QUESTIONS IDENTIFIED IN THE CONCEPT EVALUATIONS

In the course of the concept evaluations, questions were identified which were considered to be significant. These questions were contributed from NASA and contractor sources. Where possible, these questions have been answered. The locations of the data related to the questions are indicated.

Table A3-1

IDENTIFIED QUESTIONS AND RELATED RESULTS

A. ESTABLISHED BY OBJECTIVES:

1. What are the overall effects of the degree of integration of subsystems?

Discussion:

As presented in Section 10, Vol III this Interim Report, the results of integration are quite varied, but in general, the following comments apply:

- Weight improvements normally are possible.
- Reusability is only slightly improved.
- Probabilities related to unscheduled maintenance are only slightly improved.

Reference:

- (1) Interim Report, Section 10

2. What are the effects of alternate operating modes?

Discussion:

Examination of the effects of alternate operating modes indicated that these can have a significant influence. The integration of systems

results in improved flexibility. The choice of the method of redundancy utilization has a significant effect on the probabilities of unscheduled maintenance.

References:

- (1) Interim Report, Section 10
- (2) Interim Report, Section 11.2

B. IDENTIFIED FROM THIS CONTRACT, PHASE B CONTRACTS, AND AFFECTING TECHNOLOGY CONTRACTS:

- 1. What are the factors and constraints associated with cryogenics during reentry?

Discussion:

- a. Reentry heating effects on the orbit injection propulsion supply have been examined.
- b. Reentry insulation purging studies have been conducted.
- c. Reentry heat inputs to cryogenic tanks have been determined.
- d. Leakage hazard considerations have been examined.

References:

- (1) Interim Report, Section 9.2
- (2) Interim Report, Section 9.1
- (3) Interim Report, Appendix C
- (4) Interim Report, Section 9.7

- 2. What are the requirements for purging and inerting, and what types and quantities of gases are required?

Discussion:

The purging and inerting requirements are highly dependent upon the criteria and the system design.

Reference:

- (1) Interim Report, Section 9.7

3. What are the propellant acquisition requirements for the various cryogenic supply subsystems?

Discussion:

Propellant acquisition is examined extensively in the evaluations.

References:

- (1) Interim Report, Section 9.1
- (2) Interim Report, Section 9.3
- (3) Interim Report, Appendix B

C. SUBSYSTEMS AND COMPONENTS RELATED:

I Life Support/Environmental Control Supply

1. To what extent can utilization of cryogenics be employed in the environmental control system for thermal control?

Discussion:

The evaluations related to environmental control are being examined in Task 1A - Cryogenic Cooling.

Reference:

- (1) Monthly Progress Reports, August 1971 and following
- (2) Future Quarterly Reports

2. What are the effects of improvements in heat exchanger efficiencies?

Discussion:

The heat exchangers in the LSS system are found to be relatively insignificant to the system definition.

References:

- (1) Task Reports, Subcontractor Reports, Volume 2

3. What are the effects from different coolants?

Discussion:

Based upon observations, Freon 21 is preferred to FC-75 and water-glycol in the environmental control system where exchange with cryogenics is involved. This is related to potential freezing problems.

Reference:

- (1) Task Reports, Subcontractor Reports, Volume 10

II Power Generation

1. What should be the fuel cell supply pressure?

Discussion:

The fuel cell supply system is relatively insensitive to the supply pressure. This system is sensitive to the storage pressure.

Reference:

- (1) Interim Report, Section 9.5

2. What are the effects of impurities on fuel cell integration?

Discussion:

Sensitivities are relatively small.

Reference:

- (1) Interim Report, Section 9.5

3. What are the overall effects of auxiliary power unit oxidizer/fuel ratios and associated inlet temperatures?

Discussion:

The oxidizer/fuel ratios do not appear to have large effect on the supply system weights. The mixture ratio of 0.5 appears to result in slightly lower weights.

Reference:

- (1) Interim Reports, Section 9.4

4. What should be the auxiliary power unit supply pressure?

Status:

The APU supply pressure and the resulting turbine inlet pressure are dependent upon the mixture ratio and type of supply.

<u>Type of Supply</u>	<u>Mixture Ratio</u>	<u>Turbine Inlet Pressure (psia)</u>	<u>Storage Pressure</u>	
			<u>O₂ (psia)</u>	<u>H₂ (psia)</u>
Supercritical	0.5	300	800	450
	0.9	600	800	750
Subcritical	0.5	900	40	40
	0.9	900	40	40

III Orbit Injection

1. How do insulation properties effect the systems?

Discussion:

It appears from the examinations that the insulation thermal conductivities do not have a large effect on the resulting pressurization requirements. Boiloff losses are insignificant.

References:

- (1) Interim Report, Section 9.2
- (2) Interim Report, Appendix C

2. How should the feedlines be insulated?

Discussion:

A study of the temperature rise in the propellants with circulation in the feedlines indicates that vacuum-jacketed lines are not strongly justified. Insulation with conductivities equivalent to foam are sufficient. An insulation with sufficient physical properties must be developed.

Reference:

- (1) Interim Report, Section 9.2

3. What is the effect of no insulation on the oxygen feedlines?

Discussion:

The results indicated that the temperature control of the propellants in the feedlines would be extremely difficult. Circulation flowrate requirements were impractical.

Reference:

- (1) Interim Report, Section 9.2

4. Can helium be eliminated from this propulsion system?

Discussion:

Helium should be used for initial boiling suppression as tank lockup. Onboard helium for this system could be eliminated through gaseous propellant prepressurization but this is not desirable. Helium is required for engine operation.

References:

- (1) Interim Report, Section 9.2
(2) Interim Report, Section 9.7

5. What are the acceptable component leakage rates?

Discussion:

Hydrogen leakage in the atmosphere is the only significant effect. Nitrogen purging could allow up to 10,000 sccm for a penalty of only 150 lb.

References:

- (1) Interim Report, Section 9.7
(2) Interim Report, Section 11.1

6. What are the penalties for self-pressurizing liquid oxygen?

Discussion:

The results indicated a relatively small penalty as compared to hot gas pressurization, but this approach would be very sensitive to heating conditions.

Reference:

- (1) Interim Report, Section 9.2

7. Can common lines be used for venting and pressurization?

Discussion:

The results indicated that common lines are feasible.

Reference:

- (1) Interim Report, Section 9.2

IV Orbit Maneuvering

1. What are the effects of the considerations in the definition of the orbit maneuvering supply system, particularly as affecting the integrated systems?

Discussion:

- (1) Orbit maneuvering supply system tradeoff studies have been performed.
- (2) Integrated System analysis was performed.

References:

- (1) Interim Report, Section 9.1
- (2) Interim Report, Section 10

2. What are the effects of having integral turbopumps versus using APU-driven pumps for the supply systems?

Discussion:

The only feasible approach is to use pumps with electric motors. This was examined.

Reference:

- (1) Interim Report, Section 10

3. What are the effects of insulation properties?

Discussion:

Insulation materials did not significantly affect overall system weight.

References:

- (1) Interim Report, Section 9.1
- (2) Interim Report, Appendix C

4. What are the acceptable component leakage rates?

Discussion:

- (1) Parametric leakage studies indicate that helium losses are negligible, but over-pressurization from helium leakage into tanks could be sufficient to activate pressure-controlled venting.
- (2) Hazards from hydrogen leakage cannot be completely evaluated since low-leakage flame technology data are not available. Technology studies are required.

Reference:

- (1) Interim Report, Section 11.1

5. Which types of pressurization should be utilized?

Discussion:

Integrated systems require the use of helium for continuous NPSH. Gaseous propellant is applicable only to the nonintegrated subsystem.

Reference:

- (1) Interim Report, Section 9.1

6. What is the acquisition system design?

Discussion:

The acceleration levels are believed to require multiple screens. In order to reduce the size of the acquisition devices, tank-dividing bulkheads are desirable.

References:

- (1) Interim Report, Section 9.1
- (2) Interim Report, Section 9.3
- (3) Interim Report, Appendix B

7. Is an oxygen thermal conditioning unit required?

Discussion:

There appears to be no need for an oxygen thermal conditioning unit. There is sufficient hydrogen boiloff to provide oxygen tank cooling, if desired.

Reference:

- (1) Interim Report, Section 9.1

8. What is the approach and propellant requirements for line chilldown?

Discussion:

Chilldown by use of a small inlet liquid line is the best approach.

Reference:

- (1) Interim Report, Section 9.1

9. Are vacuum-jacketed lines required and what are the associated weights?

Discussion:

The results are dependent upon the cases being examined.

References:

- (1) Interim Report, Section 9.1
- (2) Interim Report, Section 10

10. What is the sensitivity up to 12 starts as compared to 5 starts?

Discussion:

These sensitivities are presented.

Reference:

- (1) Interim Report, Section 9.1

V Attitude Control Propulsion Supply

1. What are the overall comparisons of supercritical storage versus turbopumps for high-pressure attitude-control systems?

Discussion:

The comparisons indicate that the supercritical ACPS hardware weights are approximately twice as much as the subcritical hardware weights.

Reference:

- (1) Interim Report, Section 9.3

2. Should high-pressure attitude-control systems employ separate turbo-pumps or APU-driven pumps?

Discussion:

Comparisons have indicated that using pumps with electric motors produces system weights some 200 to 400 lb heavier when existing APUs are used to produce the power.

Reference:

- (1) Interim Report, Section 9.3

3. How can the effects of gaseous propellant temperature and density variations be minimized?

Discussion:

No significant progress has been made in a solution to this problem.

4. What is the propellant acquisition system design?

Discussion:

The acquisition device appearing to have significant promise is a gallery-type device with inlets containing multiple screens.

References:

- (1) Interim Report, Section 9.3
- (2) Interim Report, Appendix B

5. Can helium be eliminated from this propulsion system?

Discussion:

The instant-start capability requires helium in the subcritical systems.

Reference:

- (1) Interim Report, Section 9.3

6. Do all liquid systems appear to be competitive with the gas-gas systems?

Discussion:

It appears that the all-liquid ACPS systems are competitive with the gas-gas systems.

Reference:

- (1) Interim Report, Section 9.3

VI Components Related

1. What is the availability of components and what is the relative reusability of existing components?

Discussion:

It was determined that components are available for most of the applications and have relatively good lifetimes.

References:

- (1) Interim Report, Section 11
- (2) Task Reports, Subcontractor Reports

- 2. What are the constraints associated with lightweight plumbing?

Discussion:

Aluminum feedlines appear to be a satisfactory approach but more development is required.

References:

- (1) Interim Report, Section 11
- (2) Task Reports, Master Integrated System Report

- 3. What are the desirable approaches to reusable insulation for cryogenic feedlines?

Discussion:

Vacuum jacketing would provide the ultimate approach to insulation protection, but normally use of vacuum jacketing results in an unnecessary weight penalty. A "breathing" type system may be satisfactory for multilayer insulated lines. This system would be purged when cryogenics are in the lines in the atmosphere. Removable and replaceable foams are satisfactory for lines not holding cryogenics in orbit.

References:

- (1) Interim Report, Section 9.1
- (2) Interim Report, Section 9.2
- (3) Interim Report, Section 11.1
- (4) Interim Report, Section 11.2
- (5) Interim Report, Appendix C

4. What valve-actuation approaches could be used in various cryogenic supply system applications?

Discussion:

These were examined for each application.

Reference:

- (1) Task Reports, Subcontractor Reports